Physics Unique to a e^+e^- Linear Collider

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15 February 2001

- Introduction
- Physics Cruxes
  - Higgs mechanism
  - New Strong Dynamics
  - Supersymmetry
  - Extra Gauge Bosons
  - Space-time structure
- Conclusions

Thank you to: Andreas Kronfeld, Joe Lykken, JoAnne Hewett

Physics Goals

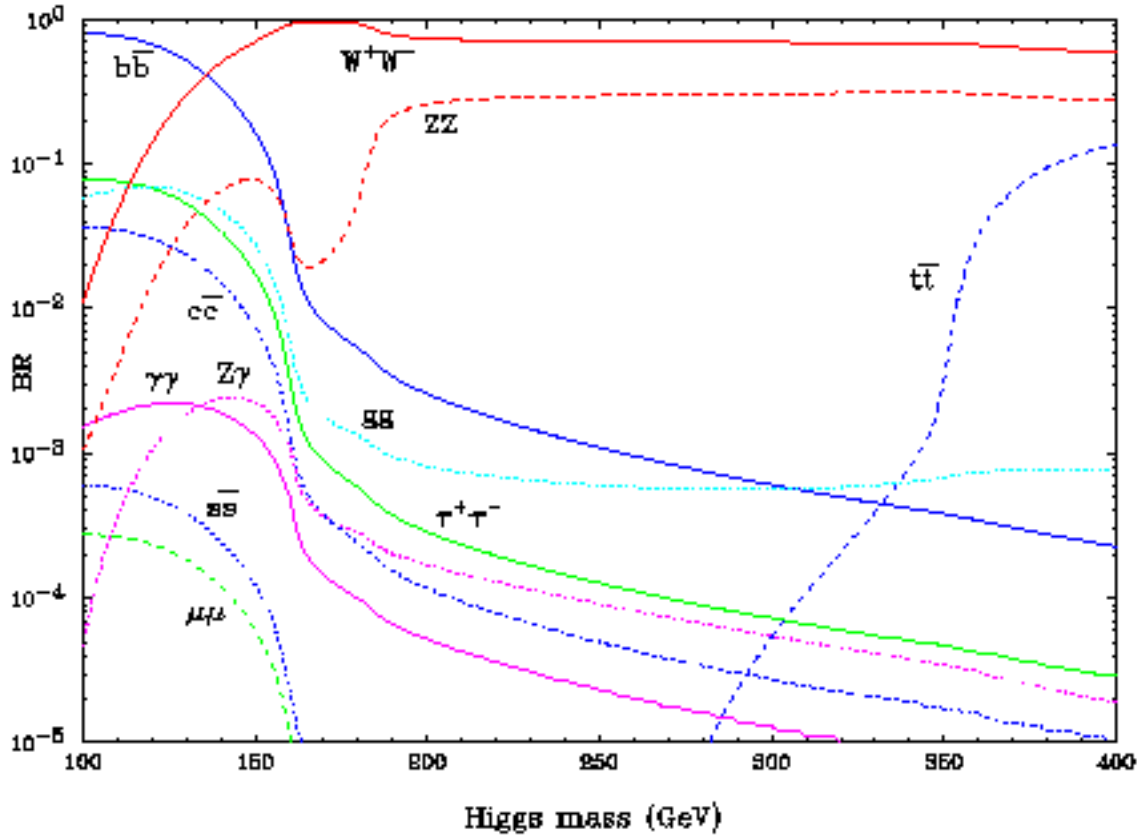
- What breaks the electroweak symmetry?
  - ▷ Experimental verification of the Higgs mechanism or alternative EWSB
  - ▷ Discovery of the physics generating the Higgs boson(s)
  - ▷ Supersymmetry and SUSY breaking, reconstruction of the fundamental theory
  - ▷ Space-time structure: exploration of extra dimensions
  - ▷ Gauge symmetries of forces, extended symmetries
- Comprehensive and high precision coverage of energy range above 200 GeV up to Multi-TeV
- Extrapolation of physics to areas far above directly reached to guide future directions
- The Linear Collider should be judged on how well it can help to understand the answers to these questions in the context of LHC!

SM Higgs Mechanism

- **Theory:** Masses of SM particles generated via SSB
  - ▷ Weak iso-doublet scalar field with non-zero field strength in the ground state, v=246 GeV
  - ▷ Gauge boson masses acquired via the interaction with a scalar field → one Higgs particle
  - ▷ Self-interaction property of the scalar field → $M_H = \sqrt{2\lambda}v$
- **Experimental verification:** Establish Higgs mechanism for generating masses of fundamental particles (talk by Andreas Kronfeld on Jan 25 2001)
  - ▷ Discovery of the Higgs boson: LEP2, TeV, LHC
  - ▷ Determination of its Mass, BR, spin-parity,...
  - ▷ Measurements of gauge and Yukawa couplings
  - ▷ Generating masses by interaction with scalar field: cplgs ∼ mass
  - ▷ Reconstruction of the Higgs potential → Measurement of the Higgs boson self-couplings

Higgs Boson

- Copious production at the LC would permit measurements of several Branching Ratios
- In the SM all masses come from interactions with scalar field, thus ratios of BR should satisfy $BR_1 : BR_2 = m_1^2 : m_2^2$
- BR to $\gamma\gamma, gg$ count charged and colored species, respectively
- $e^+e^- \to t\bar{t}H$ gives top Yukawa coupling
- Several Higgs doublets? Sum rule: $\Sigma v_i^2 = v^2$
- Comparison to LHC?



Determination of the Higgs Potential

- Reconstruction of the Higgs potential, $V = \lambda(|\Phi|^2 - \frac{1}{2}v^2)^2$ from measurements of the Higgs boson self-couplings

- Higgs self-couplings: $\mathcal{L} = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$
  - ▷ Trilinear coupling: via Higgs pair production, $e^+e^- \to HHZ$ or $e^+e^- \to \nu\overline{\nu}HH$
  - ▷ Quadrilinear coupling: via triple Higgs production, $e^+e^- \to HHHZ$ or $e^+e^- \to \nu\overline{\nu}HHH$

- The tri- and quadri-linear cplgs are related in the SM, $M_H = \sqrt{2\lambda}v$

- Measurements of the Higgs boson self-couplings and Yukawa couplings establish Higgs mechanism for generating masses of fundamental particles.

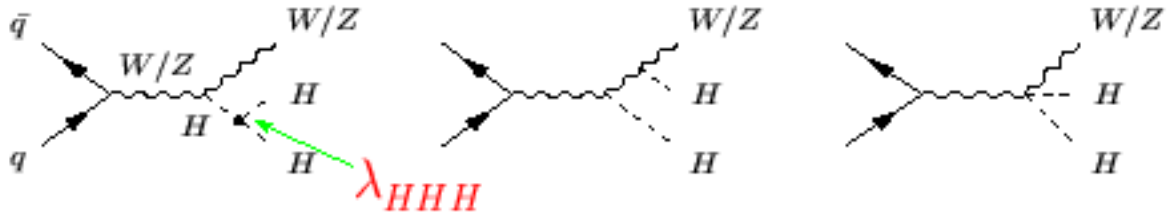
Reconstruction of the Higgs Boson Potential

- Double and Triple Higgs boson production
  - LHC
  - LC

Double Higgs Production at the LHC

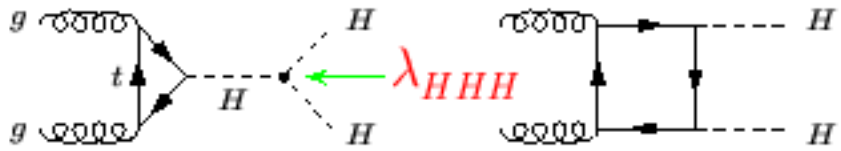
SM Production mechanisms:

double Higgs-strahlung: $q\bar{q} \to ZHH/WHH$

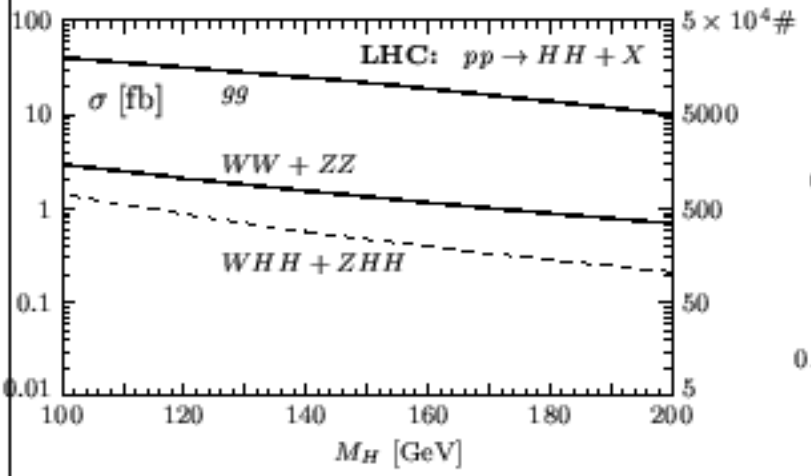


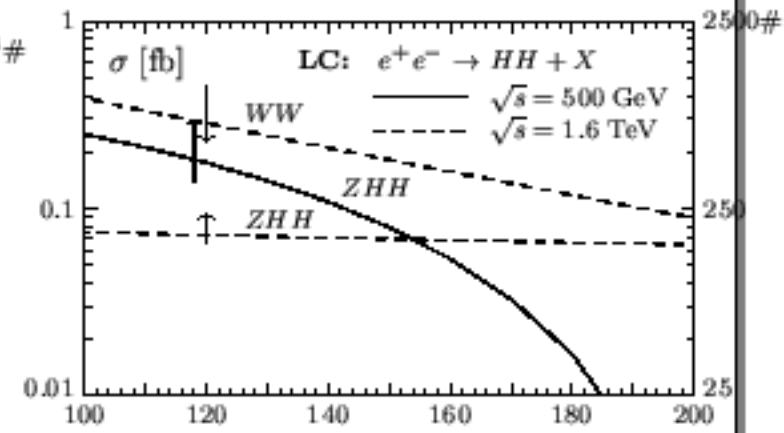
WW/ZZ double-Higgs fusion: $qq \to qqHH$

gg double-Higgs fusion: $gg \to HH$



Double Higgs Production at LHC



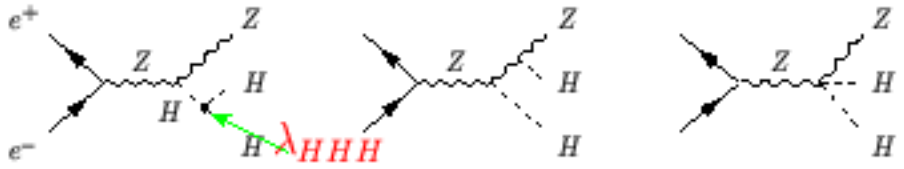


- SM Higgs Boson production characterized by very large backgrounds and tiny signal
  - Typical cross sections are of the order of 10 fb^{-1}
- High integrated luminosity needed to generate large sample of double Higgs boson events
- So far no effective way to reduce overwhelming backgrounds
- Analysis in the hadronic environment extremely difficult and there is no simulation activity on Higgs self-couplings.
- A window of opportunity exists in MSSM:
  - $H \to hh$ production for small $tan\beta$
  - $H \to hh \to \gamma\gamma b\bar{b}$ or $H \to hh \to b\bar{b}b\bar{b}$

Double Higgs Boson Production at LC

▷ **SM production mechanisms:**

double Higgs-strahlung: $e^+e^- \to ZHH$



WW double-Higgs fusion: $e^+e^- \to \bar{\nu}_e \nu_e HH$

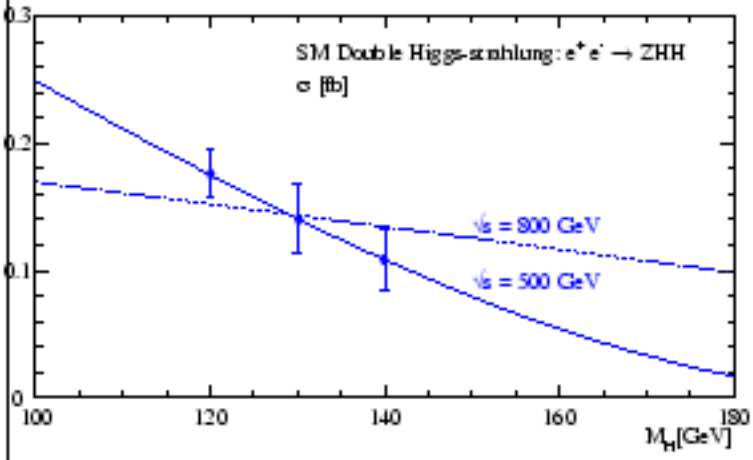
▷ Small cross sections; $\sigma_{HHZ} = 0.185\ fb^{-1}$ for $M_H \sim 120 GeV$ at $\sqrt{s}$=500 GeV; WW component even smaller at $\sqrt{s}$=500 GeV

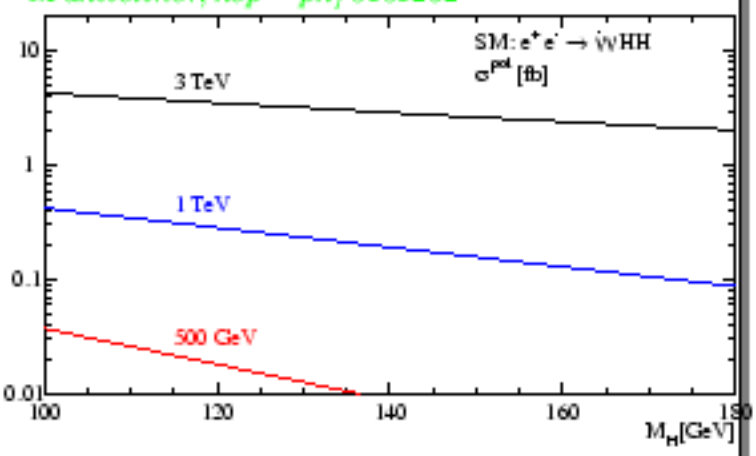
▷ Maximum cross section for $M_H \sim 120$ GeV at $\sqrt{s}$=500 GeV; only **93** signal events with $\int \mathcal{L} = 500 fb^{-1}$; large sensitivity to λ_{HHH}

▷ Backgrounds from other EW processes present

▷ 4-/6-jet bkgs and small σ_{HHZ} makes the analysis challenging **(S/B$\sim 10^{-5}$)**

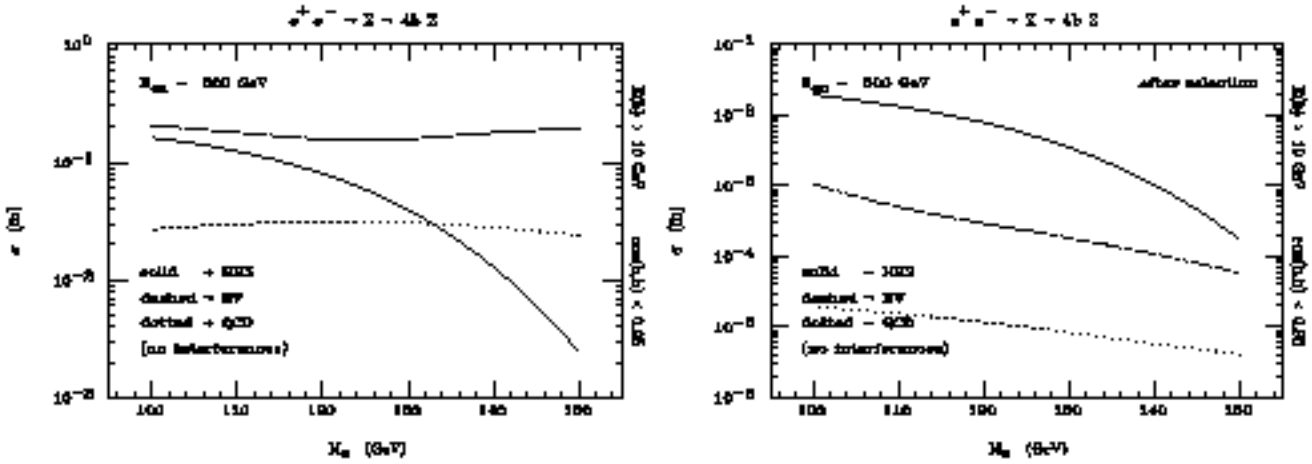
Muhlleitner, hep − ph/0101262





Double Higgs Boson Production

- **Signal signature: Z+4 b-jets**
  - ▷ **b-jet energy:** $E(b) > 10$ **GeV**
  - ▷ **separation of 2 b-jet combinations:** $\cos\theta_{(b,b)} < 0.95$
  - ▷ **high efficiency and purity of b-tagging algorithm**



Miller, Morretti

- **Additional selection:**
  - ▷ 2-jet mass combinations consistent with the Higgs mass or $Z \to bb$
  - ▷ Event shape variables combined with a NeuralNet

- **4 b-jets and $Z \to q\bar{q}$ or $Z \to \ell\bar{\ell}$ combined with excellent tagging and detector reconstruction results in:**
- $\delta\lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH}} \sim 0.22 - 0.18\%$ Castanier et al., hep-ex/0101028 **@ $\sqrt{s}$=500 GeV, $\int \mathcal{L}$ = 1-2 ab^{-1}**

Reconstruction of Higgs Boson Potential at LC and LHC

- **Double Higgs Production:**
  - ▷ **Small SM signal swamped with irreducible $b\overline{b}b\overline{b}$ backgrounds from EW or QCD processes**
  - LHC:
  - ▷ QCD Backgrounds can be reduced to the same level as the signal, still detectable, but very small.
  - ▷ Some window of opportunity left in the MSSM, $m_H > 2m_h$, when the double Higgs production is enhanced due to the resonant production
  - LC:
  - ▷ Double Higgs signals and Higgs self-couplings can be studied in an essentially background free environment.
- **Triple Higgs Boson Production:**
  - ▷ Quadrilinear coupling unmeasurable at LC and LHC with expected luminosities.

Beyond the SM Ideas

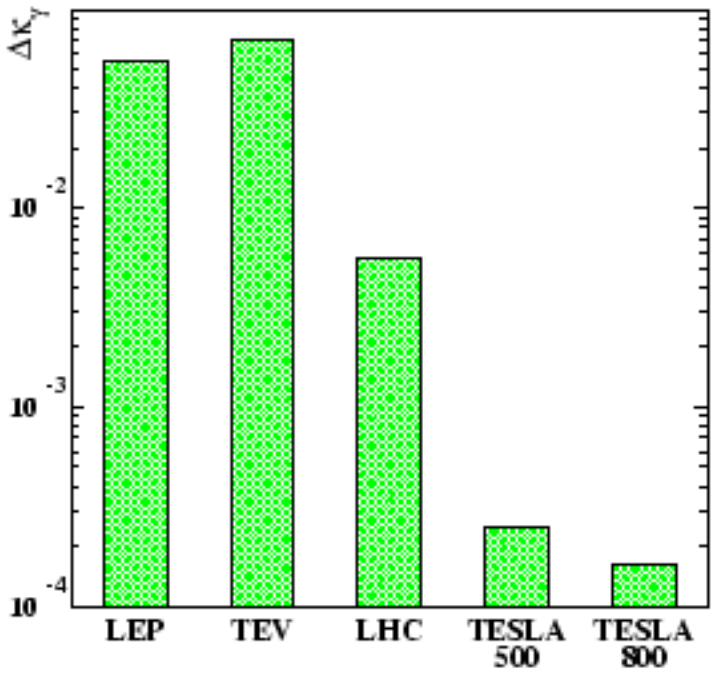
- Other mechanisms of EWSB:
  - ▷ New Strong Dynamics
    - technicolor, strong WW scattering
    - composite Higgs boson, topcolor
  - ▷ Supersymmetry
    - minimal
    - non-minimal
  - ▷ Extra dimensions
    - large
    - warped
- ...all predict a rich spectrum of new particles

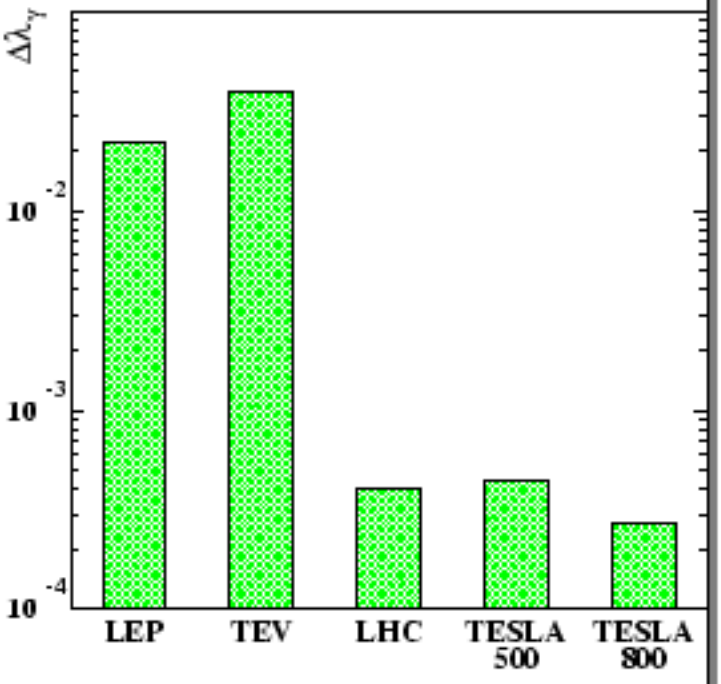
Strongly Interacting W & Z Bosons

- **Without a fundamental Higgs boson with $M_H < \mathcal{O}(1\ \text{TeV})$ an alternative scenario of EWSB provided by new strong interactions**
- **EW gauge bosons become strongly interacting at energies above $\mathcal{O}(1\ \text{TeV})$ to comply with unitarity requirements of the $W_L W_L$ scattering**
  - ▷ new strong interaction characterized by a scale Λ^* of order $\mathcal{O}(1\ \text{TeV})$
  - ▷ novel resonances predicted in the $\mathcal{O}(1\ \text{TeV})$
- **Such scenarios can be analyzed in the elastic scattering of W bosons at the energies $\sqrt{s} \sim 1$ TeV at high energy LC and LHC**
- **Properties of the new resonances and measurements of the gauge boson couplings could reveal the underlying strong interactions**
- **At LC, WW interactions can be investigated in reactions: $e^+e^- \to \mathrm{W}^+\mathrm{W}^-\nu\overline{\nu}$ and $e^+e^- \to \mathrm{W}^+\mathrm{W}^-$**
  - ▷ **all possible combinations of isospin and angular momentum can be realized in the first process in e^+e^- and e^-e^-.**
    - ▷ cross sections small unless resonances are formed.
  - ▷ **essential to have another way to probe modes with composite Higgs bosons (via precision measurements of Triple GC and Quartic GC)**

Gauge Bosons - Triple Gauge Couplings

- Accuracy of the parameters describing the WWZ and WWγ vertices:
  - ▷ SM precision on κ_γ which contributes to the W anomalous magnetic dipole moment, is of the order $\Delta\kappa_\gamma \sim (10^{-3} - 10^{-4})$ (including radiative corrections)
  - ▷ the expected effects of new strong interactions: few parts in 10^{-3}
- Estimated TGCs limits are of the order of EW radiative corrections; but they scale with integrated luminosity
- Further theoretical studies of the systematics of non-leading corrections will be useful.
- The limits on the TGCs translate to physics reach of $\Lambda_* \sim 5$ TeV $> \Lambda_{EWSB} \sim 3$ TeV for the EWSB sector in W pair production, confirming that any reasonable scenario of the symmetry breaking can be probed, since new physics is expected to occur below Λ_{EWSB}.





Supersymmetry

- Best motivated extension of the Standard Model
  - ▷ connection to gravity
  - ▷ grand unification
  - ▷ mitigates the hierarchy problem and predicts $sin^2\theta_W$.
  - ▷ Mass scale of SUSY, $M_{SUSY} \sim 1$ TeV
- SUSY exploration:

▷ LHC analyses:

- specific paths of cascade decays can be followed
- mass differences measured well
- can distinguish model types

▷ In LC:

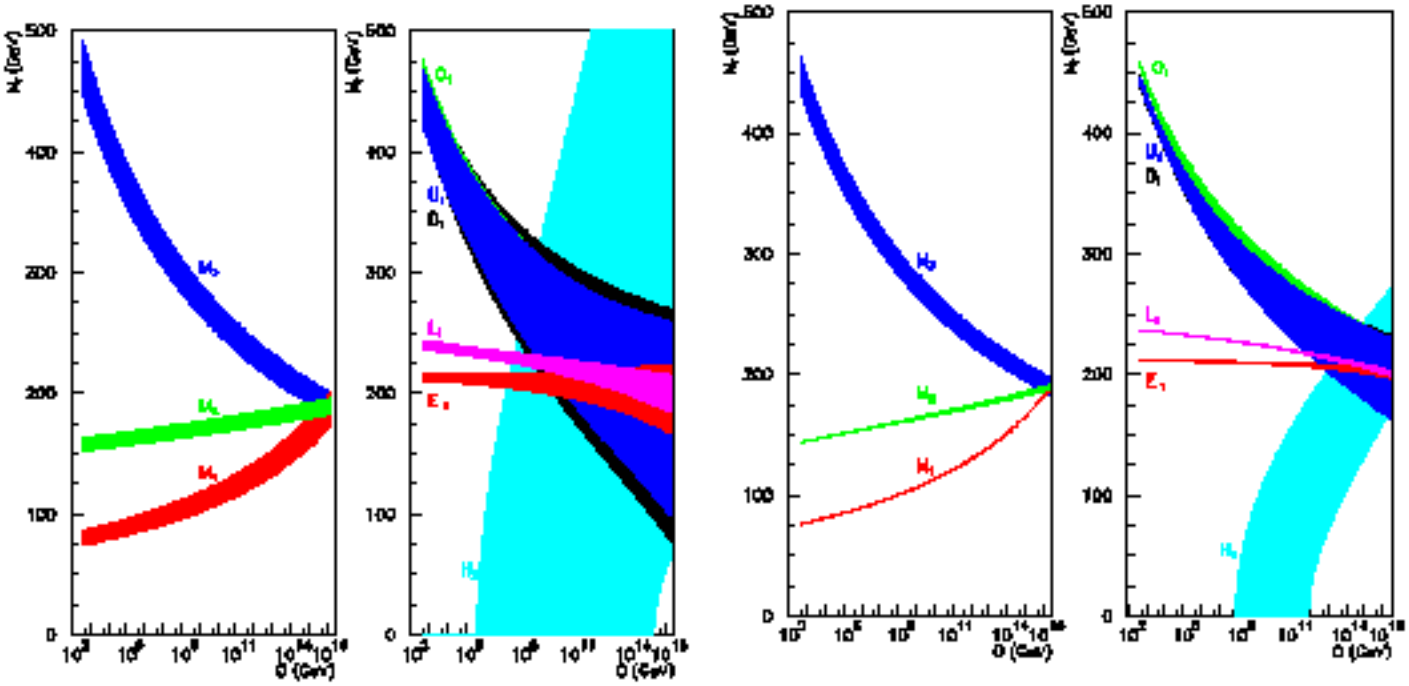
- model independent comprehensive reconstruction of the entire SUSY spectrum: masses, production and decay, spin-parity
- individual production of sparticles, robust, very precise picture, stable extrapolations to high scales
- measurements of couplings to prove SUSY and to distinguish SUSY from other models
- fully explore the SUSY parameters
- upgrade to higher energies is probably needed.

- Analysis of SUSY breaking - reconstruction of the fundamental theory $\rightarrow$ high scales?

Reconstruction of the Underlying Fundamental Theory

- Extrapolate from the basic parameters at the EW scale to the fundamental theory at high scale
  $\Longrightarrow$ in most studies of SUSY models assumptions are made at a high energy scale.
- Start from the measurements (with uncertainties!) done at lower energies and extrapolate to higher energies using RGE.

SUGRA; LHC uncertainties only SUGRA; LC and LHC uncertainties

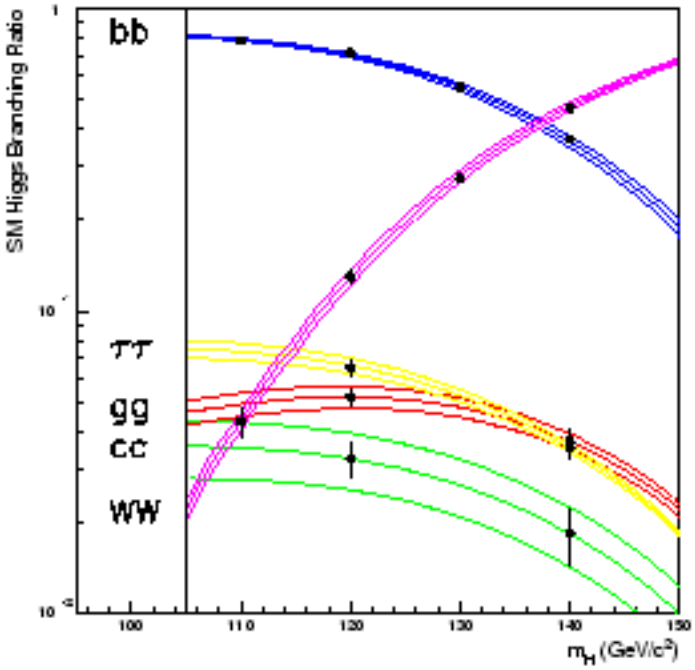


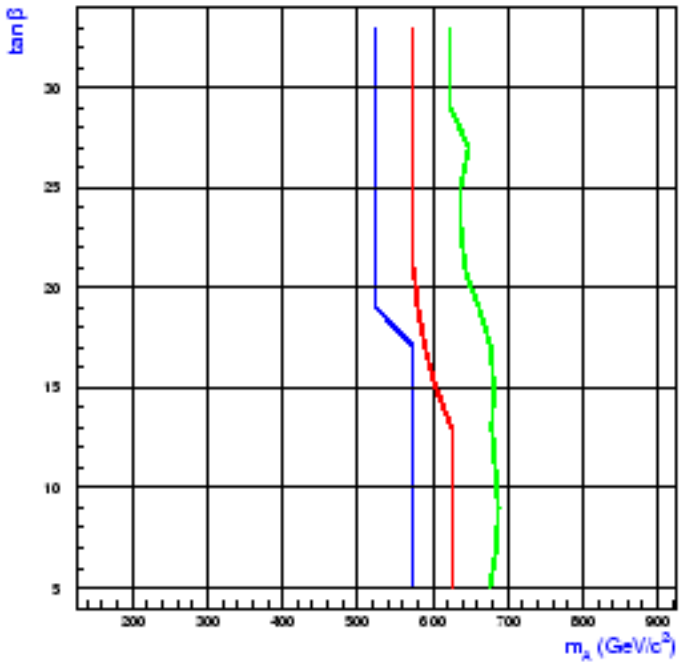
Blair, Parodi, Zerwas

- Precise data are essential for stable extrapolations to high energy scales $\Longrightarrow$ High precision of linear colliders opens perspectives on particle physics near the Planck scale

Distinguishing the SM H and MSSM h

- MSSM: h, H, A, $H^{\pm}$ SM: H_{SM}
- If M_{SUSY} and M_A are large, a neutral Higgs boson may be the only new object observed at Tevatron, LHC and LC.
- Its SM/MSSM origin may be indirectly inferred from the precise determination of the Higgs profile, BR, couplings and Γ.
- Many theoretical uncertainties:
  - SM Higgs cplgs to quarks limited by m_q and to gluons by α_S
  - MSSM Higgs cplgs to quarks limited by corrections from gluino loops
- Sensitivity to SM/MSSM from determination of BR shown as upper bounds of the MSSM solutions distinguishable from the SM BR predictions. TESLA L = 500 fb^{-1}

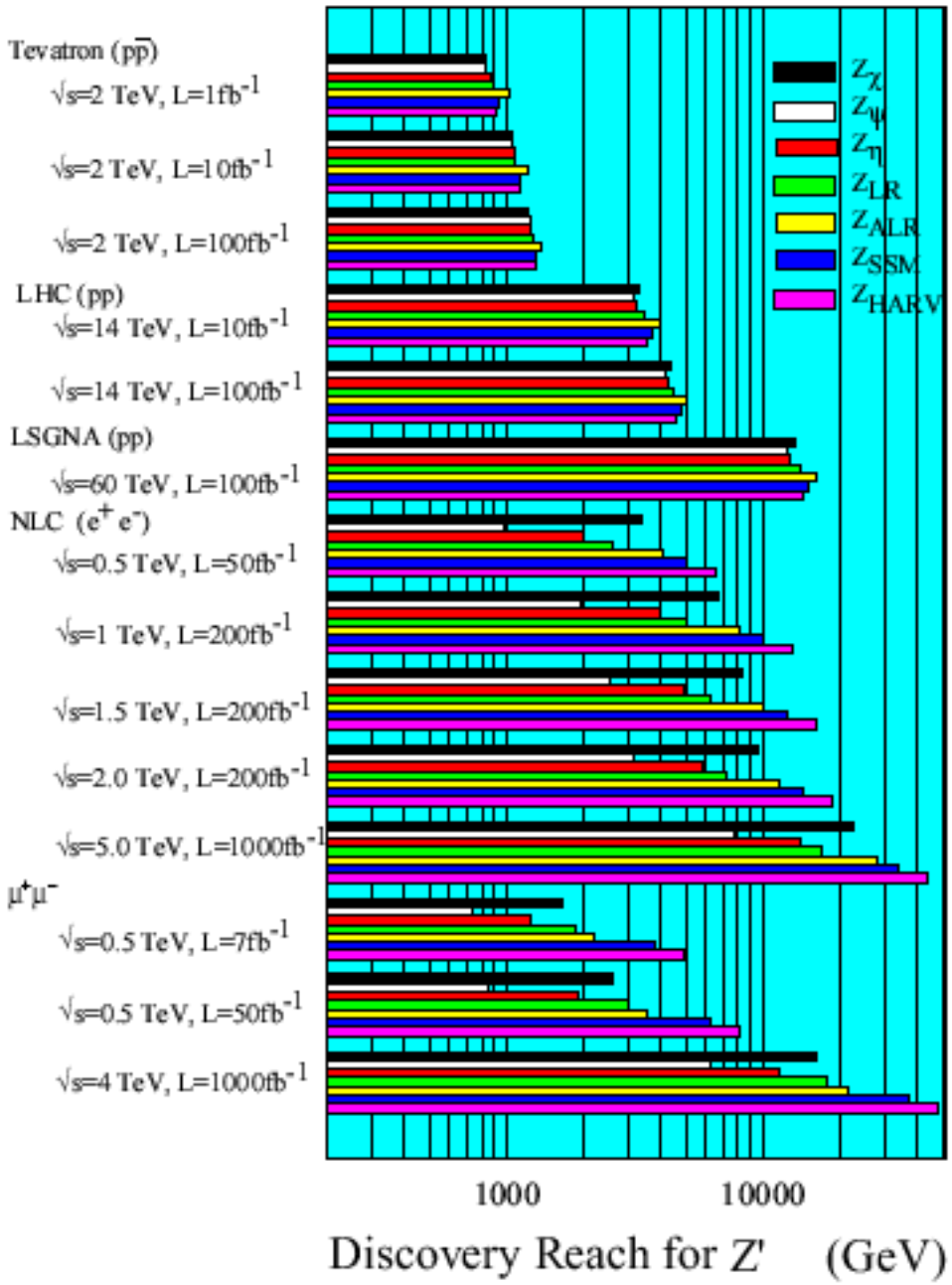




New Phenomena

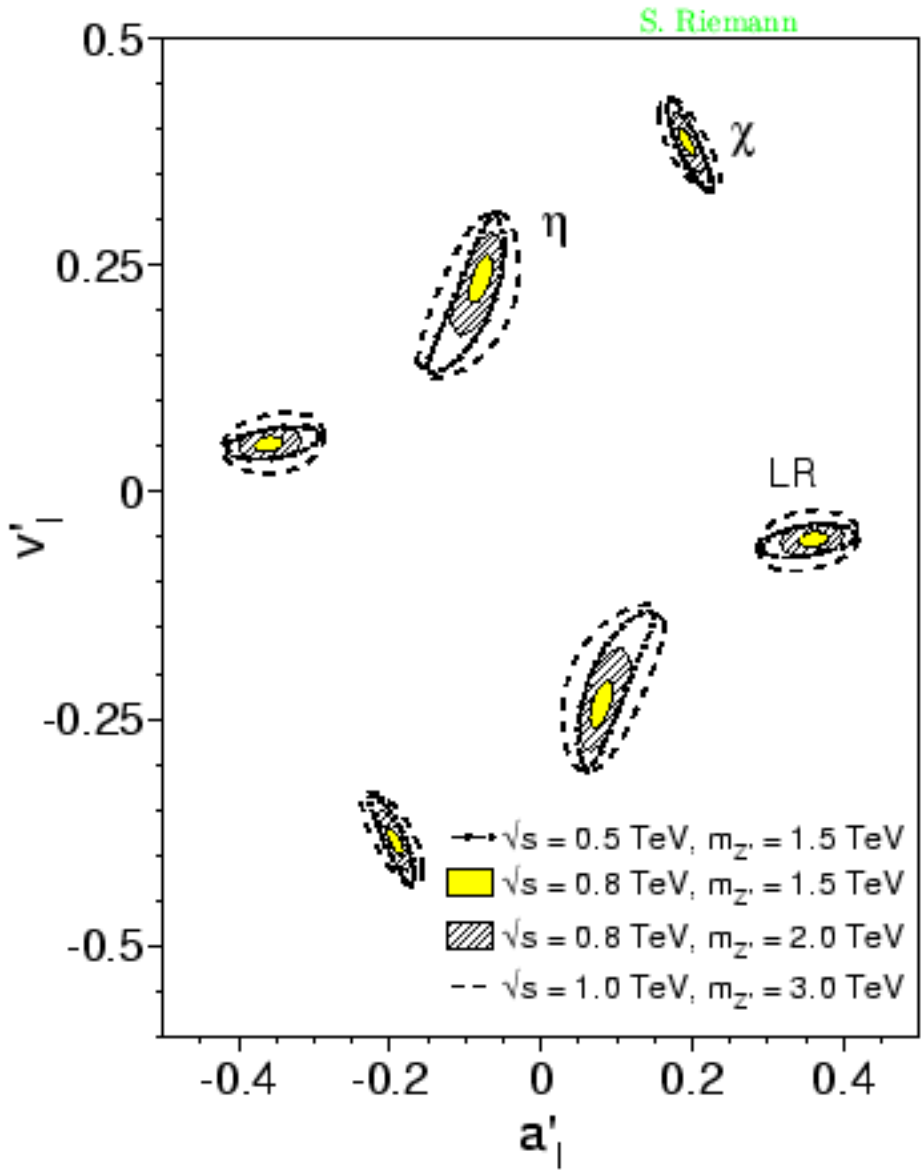
- SUPERSYMMETRY need not to be realized in nature
- SUSY can be augmented by other new physics
- Either way the LC or any other machine need to be prepared for unexpected!
- Formal theory used as a guide to phenomenologically rich ideas:
- Extended Gauge Theories: SO(10), E6
  new gauge bosons, new fermions
- Instead of adding extra fields (SUSY,...),
  add extra dimensions to the universe.
- Approach hierarchy from a geometric point of view.

Search for Extra Gauge Bosons

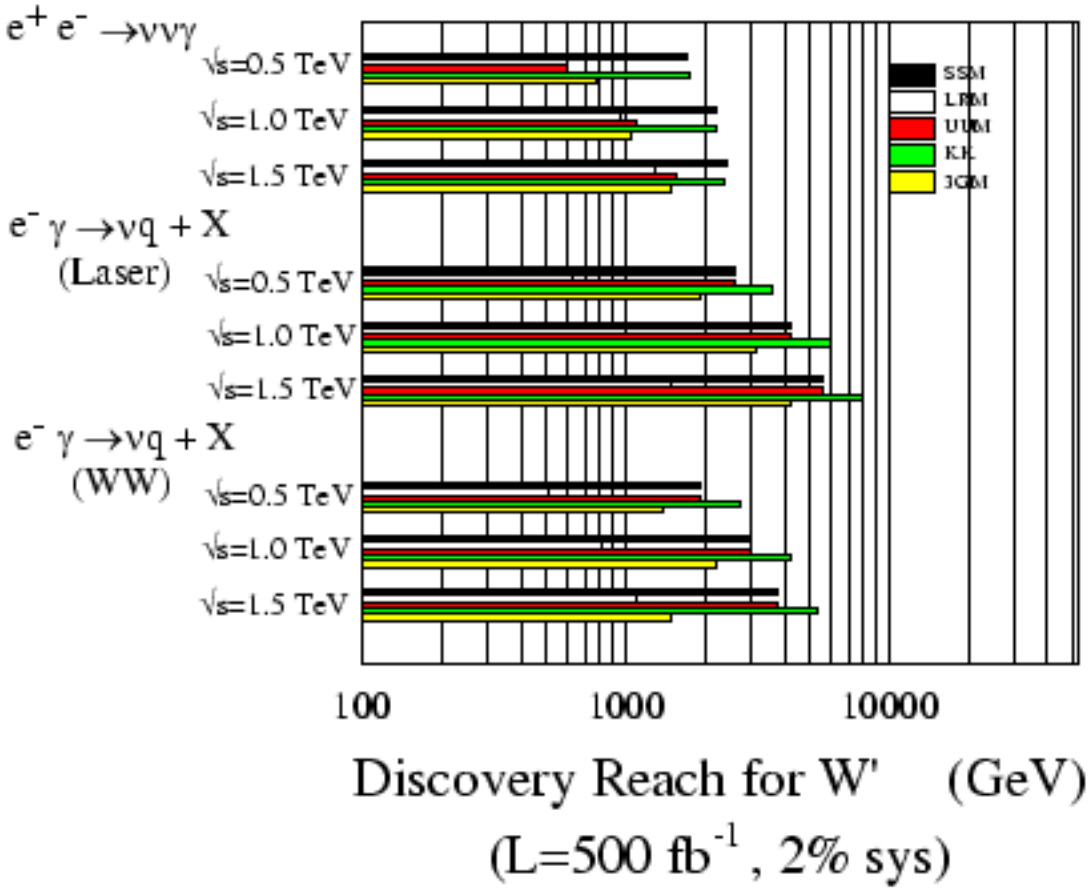


Extra Gauge Bosons - Couplings

- Resolution power for different $m_{Z'}$ based on measurements of leptonic observables at $\sqrt{s} = 500,\ 800,\ 1000$ GeV with a $\mathcal{L}_{\rm int} = 1$ ab^{-1}
- Leptonic couplings of the Z' correspond to the various models.



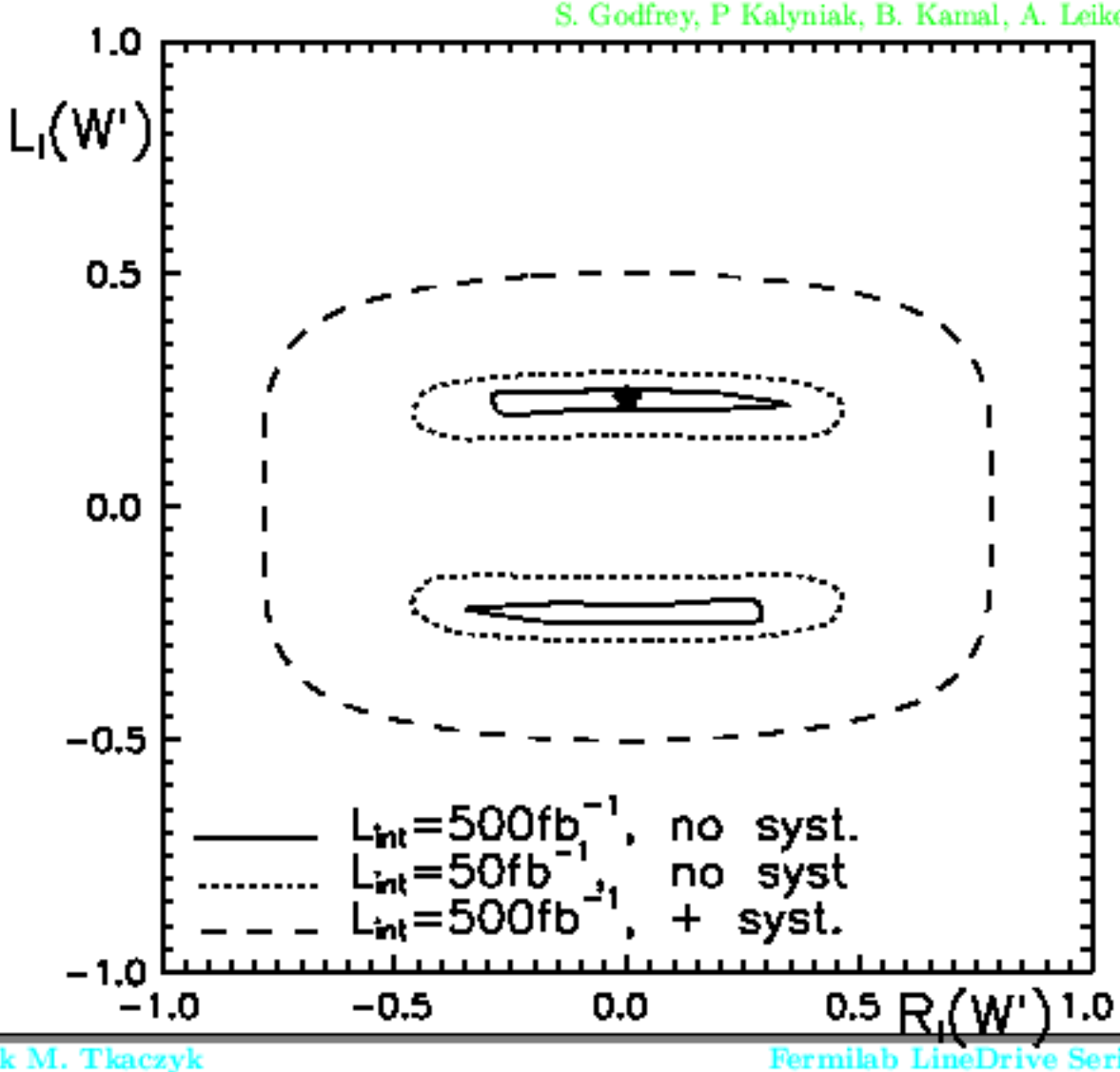
W′ Studies at LC



Extra Gauge Boson - W′ Studies

- Analysis of W′ production in $e^+e^- \to \nu\bar{\nu}\gamma$ at $\sqrt{s} = 500\ GeV$
- Sensitivity to W′ masses up to several TeV, depending on energy, luminosity and models.
- Constraints on W' couplings for $m_{W'} = 1.5\ TeV$ using combinations of σ and A_{LR} measured in polarized beams, 90% for e^- and 60% for e^+.
- A systematic error of 2% (1%) was used for σ (A_{LR}).

S. Godfrey, P Kalyniak, B. Kamal, A. Leike



Space Time Structure

- Novel approaches to solve the hierarchy problem in the SM, between the Planck scale, the apparent scale where gravity becomes strong, and the EW scale of particle physics.

- Several scenarios proposed in which space is extended by extra dimensions, compactified at a radius R.
  - ▷ towers of massive Kaluza-Klein states

- Gravity may become strong in extended space already at TeV scale and the hierarchy problem is non-existent.
- Gravity appears weak in ordinary 4-dim space as we only observe its projections onto the wall.

- Inspired by String Theory, the effective Planck scale can be identified with the string scale M_s;
- Very little known about the compactification.

- Many variants of the model (metric of compactified space, fields on the brane, in the bulk, etc...)

Extra Dimensions

- **Large Extra Dimensions** (Arkani,Dimopoulos,Dvali)
  ($n = 2$ as large as $R \sim 1\ mm$; $n = 6$ $R \sim 10\ fm$)
  - **SM stuck on 4-dim wall, at least up to E $\sim$ 1 TeV**
  - **real emission of gravitons $e^+e^- \longrightarrow \gamma G$**
  - **virtual exchange of gravitons $e^+e^- \rightarrow f\bar{f}$**
- **Warped via Localized Gravity** (Randall,Sundrum)
  - **weak scale generated from Planck scale via warp factors**
- **Explore structure of space-time manifold (Non-Commutative FT)**
  - **conventional coordinates are represented by non-commuting operators.**

- **In some models SM particles can be in the bulk**
- **Each scenario predicts a distinct set of signatures at $\sqrt{s} \sim 1$ TeV (KK towers interact with SM fields)**
- **Future Accelerators can test these ideas and possibly yield information on the geometry of the extra dimensions of the universe (number, size, curvature,...)**

Extra Dimensions

- **Phenomenological consequences at LC:**

▷ $e^+e^- \to \gamma \not{E}$

  ▷ radiation of KK gravitons

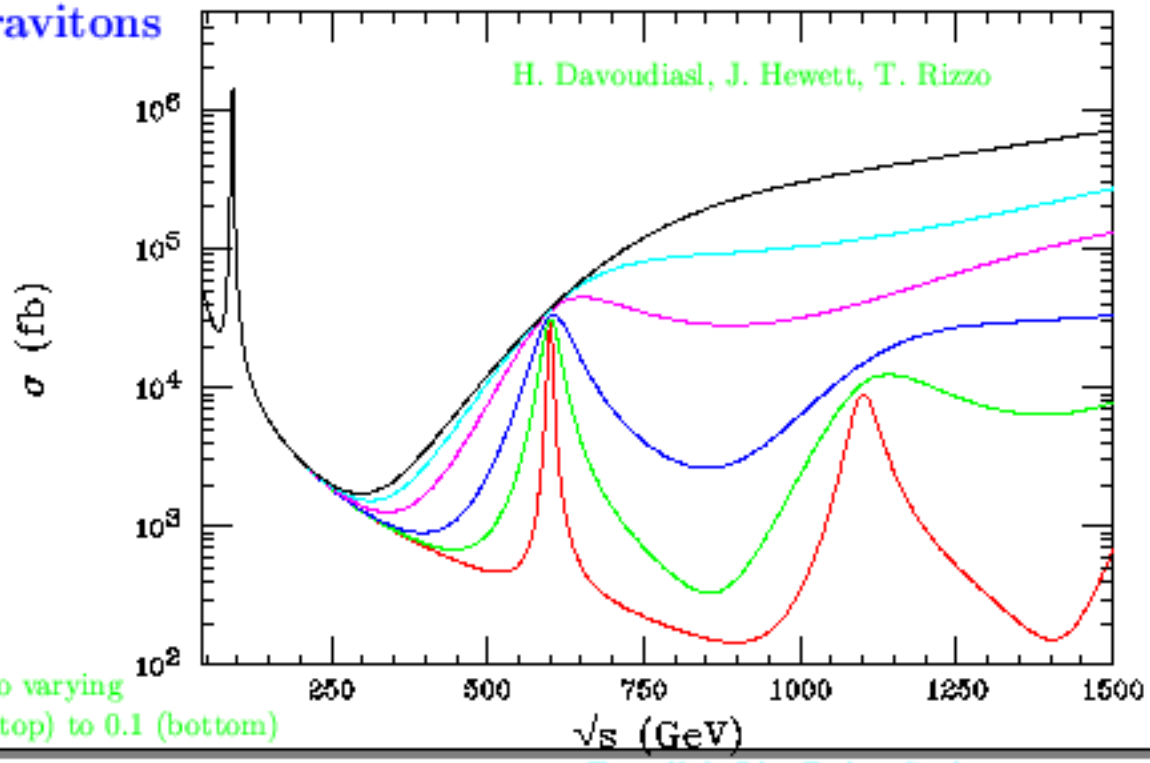
  ▷ sensitive to M_S and N

▷ $e^+e^- \to f\overline{f}$

  ▷ exchange of gravitons

  ▷ sensitive to M_S and spin 2

- **The precise control of SM reactions achievable at the LC makes these measurements possible.**
- **Through angular distributions at LC can provide information on physical nature of KK towers.**
- **Cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of KK gravitons**

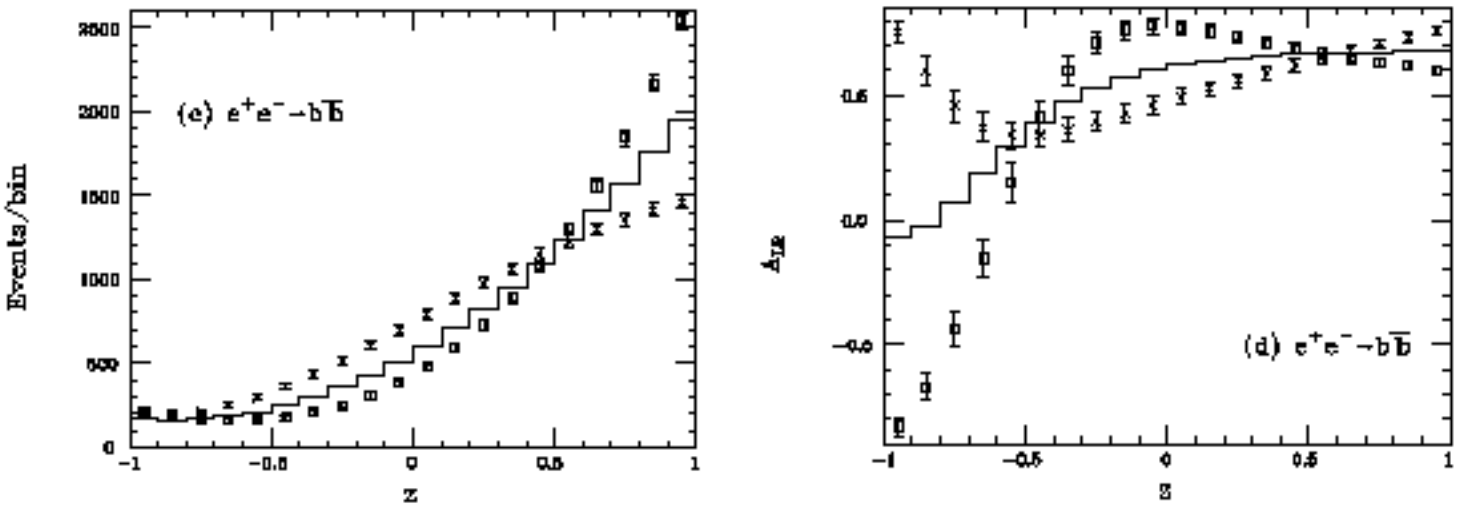


Curves correspond to varying warp factor from 1 (top) to 0.1 (bottom)

Indirect Tests of Extra Dimensions in $e^+e^- \to f\overline{f}$

- Angular distributions and polarization asymmetries become sensitive probes of the spin of new particles
- Two observables: bin integrated angular distribution and Left-Right asymmetry for the process $e^+e^- \to b\bar{b}$ at $\sqrt{s} =$ 500 GeV; SM shown as a solid histogram, while points are for M_s=1.5 TeV with $\lambda = \pm 1$ for specific models.

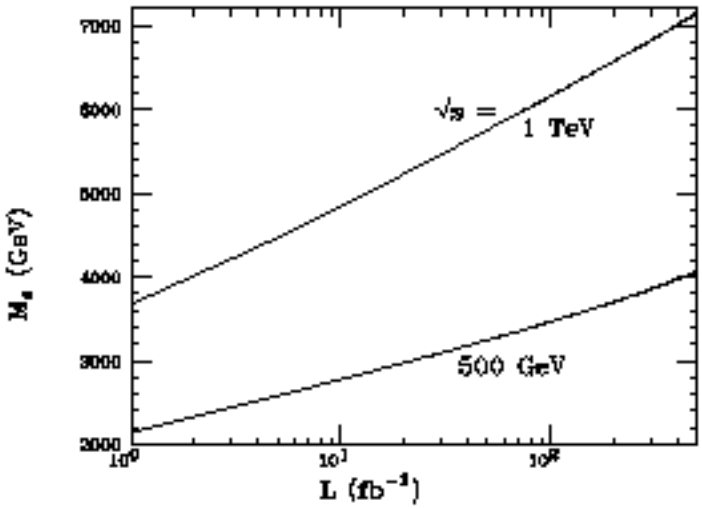
J. Hewett, hep-ph/9811356

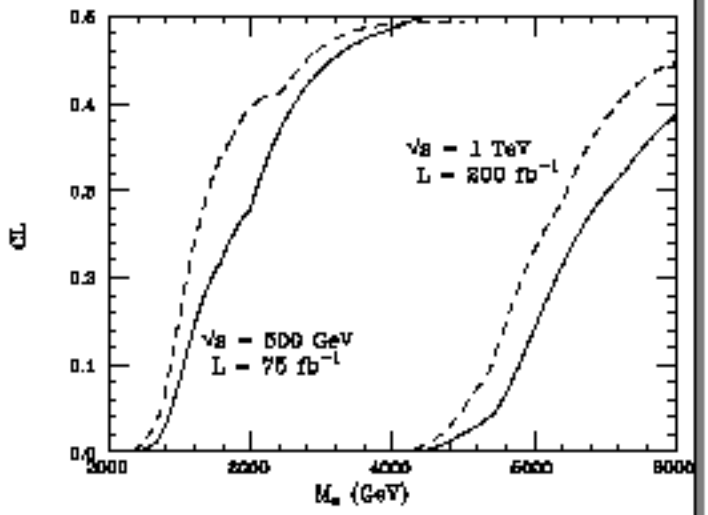


- Differential cross section for the process $e^+e^- \to f\bar{f}$ for Spin-2 Graviton exchanges contains both cubic and quartic terms in $z=\cos(\theta)$
- Combined fit of angular distributions of kinematically accessible $f\overline{f}$ states, as well as τ polarization
- 60% efficiency for heavy quark tagging, P_{e^-} = 90%, ISR effects included
- Observed statistically significant signal for Graviton exchanges.

Indirect Tests of Extra Dimensions in $e^+e^- \to f\overline{f}$

- Potential search reach of the M_s, a scale at which Gravity becomes strong

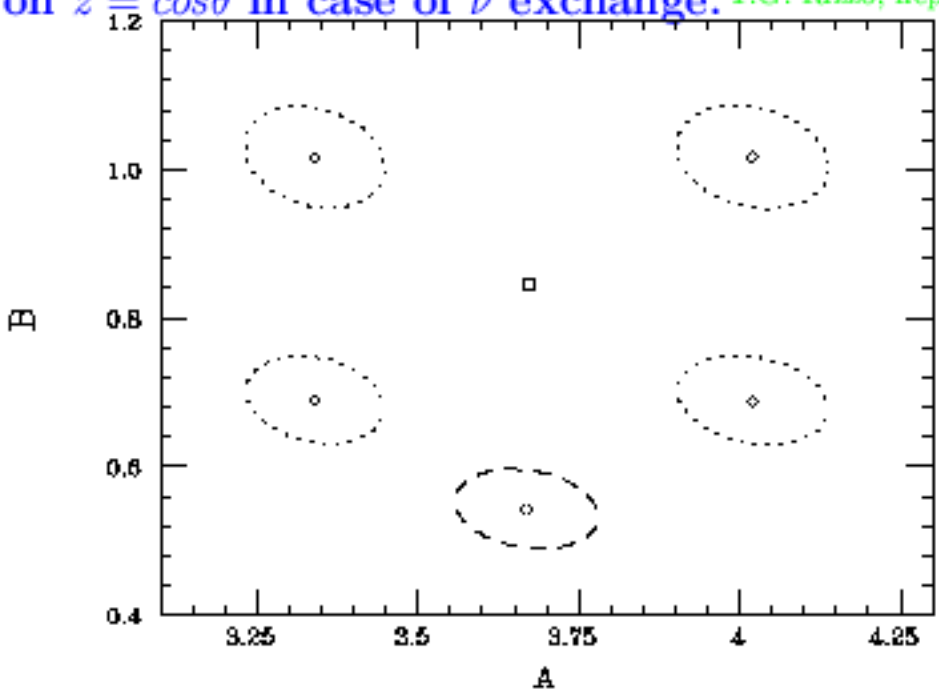




- Qualification of the extent to which Spin-2 exchanges are distinguishable from other new physics sources
- Perform a fit to functions expected for new vector boson exchanges
- Observed poor quality of the fit up the discovery limit ($M_S \sim 5\sqrt{s}$)
- Particular deviations induced by Spin-2 Graviton exchanges can be distinguished from those due to lower spins, such as new vector bosons (Z') or scalar-$\tilde{\nu}$ in R-parity violating models, for string scales up to discovery limit.

Indirect Tests of Extra Dimensions in $e^+e^- \to f\overline{f}$

- Discrimination between extra gauge boson Z' and $\tilde{\nu}$ exchanges of Spin-1 and Spin-0 particles
- Explore the influence on the angular distributions
- Two-parameter fit of the simulated data performed to a trial distribution of the form: $\sim A(1+z)^2 + B(1-z)^2$
- In the SM and any Z' cases A,B are constant, B depends on $z = cos\theta$ in case of $\tilde{\nu}$ exchange. T.G. Rizzo, hep-ph/9907344



- All 5 regions are statistically well separated from each other.
- Clearly distant solutions from the SM point
- In case of $\tilde{\nu}$ exchange the value of A is in agreement with the SM, while in Z' case the A,B are altered.

Signals of Brane Fluctuations

- Extra dimensions with Branes offer a new explanation of the hierarchy problem.

- Non rigid Branes
  - To control the position of the Brane in all dimensions new scalar fields are introduced ('Branons')
  - Branons can interact with particles on the brane
  - Their signature is a rise to $\not{E}$ signal in $e^+e^- \to \gamma\not{E}$
  - Branon properties (energy and angular spectra) similar to KK gravitons propagating in 6 extra dimensions - difficult to detect.

- Elastic Fluctuations of Branes (Nylons)

- Interactions of Branons and Nylons with each other and SM fields provide interesting testable consequences which can be studied at Future Colliders in time for a Snowmass meeting...

Conclusions

- LC can make some important measurements which can't be made elsewhere.
- The cleanliness, flexibility, and versatility of the LC compensate the higher and broader reach of the LHC.

- Essential elements of Higgs mechanism can be well established.
- SUSY particle spectrum and breaking mechanism can be analyzed experimentally.
- Structure of space-time can be probed at short distances.
- Extended gauge symmetry theories can be explored.

- Difficult to anticipate how many of new particles have mass below/above 1 TeV, and value of the LC increases with energy, in the absence of a signal.

- All phases of e^+e^- linear collider facility, $\sqrt{s} = 500$ GeV - multi-TeV and high luminosities promise new deep insight into the secrets of Nature!